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BRIEF COMMUNICATION

Symmetric extraction of positive and negative ions from electron beam-generated ion–ion plasmas

S G Walton and R F Fernsler

Plasma Physics Division, US Naval Research Laboratory, Washington, DC 20375, USA

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Abstract
Ion–ion plasmas are plasmas in which the dominant negative charge carriers are negative ions rather than electrons, and these plasmas are believed to have certain advantages in a number of applications. Many applications require ion energies of 10 eV or more, which is well above the expected energy of ions leaving ion–ion plasmas. The techniques used to achieve these energies in electron-rich plasmas must be modified to work with ion–ion plasmas. This paper describes a technique for producing alternating fluxes of positive and negative ions to a substrate. With the described circuit, the fluxes can be equivalent in either magnitude or peak energy.

In ion–ion plasmas, negative ions replace electrons as the dominant negative charge carrier and as such, ion–ion plasmas provide new capabilities. Because free electrons are nearly absent, the properties of ion–ion plasmas differ notably from conventional electron-rich plasmas. In particular, when the plasma comprises two identical ion species of opposite charge and no electrons, the plasma potential falls to zero, the flux of those species diffuse toward the walls at the ion temperature, and positive and negative ions leave the plasma in equal numbers.

The extraction of equal numbers of positive and negative ions from plasmas is thought to be useful in a number of applications. In plasma-based microelectronic device fabrication, for example, the dissimilar response of electrons and positive ions leads to surface charging in high-aspect-ratio features. Anisotropic fluxes of positive and negative ions to substrate surfaces are expected to alleviate this problem [1–3]. The delivery of high-energy negative ions might also be useful for ion implantation [4] and for thruster applications [5]. While the negative ion density can be substantial in discharges produced in oxygen or halogen containing gases [6], negative charge is still carried mainly by the hot and mobile electrons. These plasmas charge so as to retard the flow of electrons from the plasma and thereby maintain quasineutrality within the plasma. Hence, the relatively cold negative ions are confined by the plasma potential and therefore never reach the walls or substrates. Instead, most negative ions are destroyed through mutual neutralization with positive ions inside the plasma.

In many applications that would benefit from the use of ion–ion plasmas, the flux of ions as they leave the plasmas should be anisotropic, and the energy of the ions should exceed some minimum energy that is well above thermal energy. Such mandates require accelerating the ions with electric fields. However, these fields introduce the possibility that the ion–ion plasma will be altered or destroyed. Plasma instability and electron heating are of particular concern.

In this work, we describe an approach for extracting and accelerating nearly equal fluxes of positive and negative ions onto two surfaces from an ion–ion plasma without substantially altering the plasma. The ion–ion plasmas are produced through electron beam ionization of a highly electronegative gas. Beam-produced plasmas have an unusually low electron temperature [7], and this results in an unusually large attachment rate in certain halogen-based gases like SF_6 [8]. The conditions for ion–ion plasma formation are thus easily achieved. We previously demonstrated the production of electron beam-generated ion–ion plasmas as well as the extraction of alternating fluxes of positive and negative ions using a low voltage, low frequency signal [9, 10]. The frequency must be low enough for the ions to have time to fully

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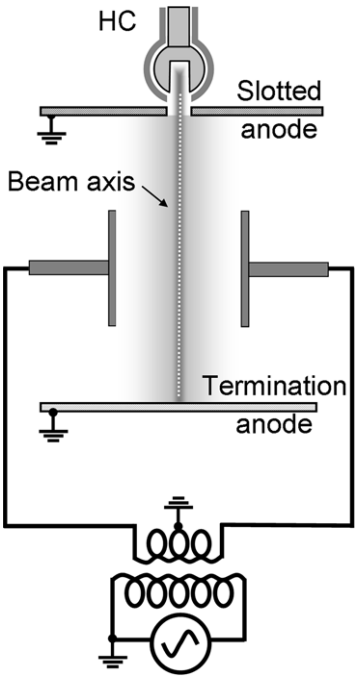

Figure 1. Schematic of experimental apparatus and biasing circuit.

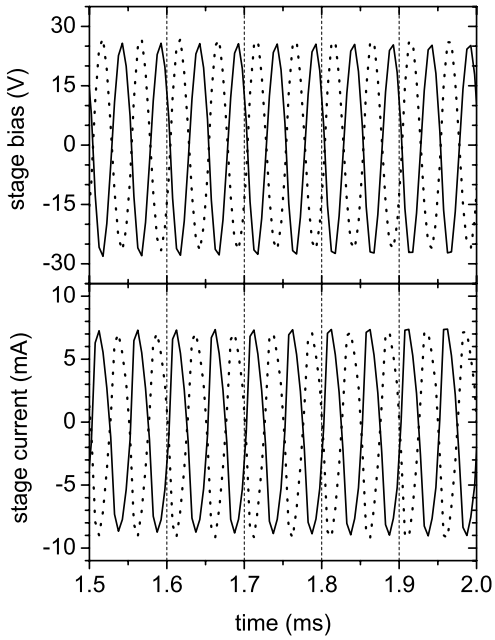

Figure 2. Measured voltage and currents in an ion–ion plasma produced in mixtures of argon and SF6 plasma using system of figure 1. For these measurements, the center tap of the secondary is grounded. Note the symmetry in measured voltage and slight asymmetry in measured current. The two curves refer to the two stages.

respond to the applied voltage, typically well below the ion plasma frequency; by contrast, the frequency used in electron-rich plasmas is usually well above the ion plasma frequency. Although discharges (i.e. the use of applied electric fields to generate the plasma) can also produce ion–ion plasmas, they occur only in the afterglow of modulated plasmas or far from the source. Thus, the ion fluxes are low and/or short in duration, and so discharge-produced ion–ion plasmas are limited in their utility.

The ability to generate ion–ion plasmas in a semi-continuous manner has allowed us to study the required apparatus and methods in detail and thereby to achieve a well-controlled extraction of ions in terms of both intensity and energy. For this work, we used two planar electrodes, located an equal distance from the ion–ion plasma center. A low frequency, sinusoidal signal was applied across the two stages through a transformer. A schematic of the experimental setup and circuit is shown in figure 1.

The production and verification of ion–ion plasma formation was described in [9, 10], and that procedure is generally followed here. Briefly, a well-defined ion–ion plasma is produced by injecting a high-energy (2 keV) electron beam into the background gas mixture of argon and SF_6 at pressures of 50 mTorr. The beam generates large numbers of free electrons through impact ionization, but the temperature of the electrons is sufficiently low that they quickly attach to SF_6 (or its daughter fragments). In order to maintain a constant beam thickness over the length of the system, a magnetic field (>150 G) is applied. This field also serves to slow the outward diffusion of plasma electrons, thereby increasing the probability they will attach to form negative ions. Of course, it is not until the attachment rate is comparable to the ionization rate that ion–ion plasmas are formed and negative ions can be extracted. We have found this occurs when the relative concentration of SF_6 is about 50% or more. The electrode or stage configuration used in this work (figure 1) consists of two opposing stages of identical surface area (79 cm^2) positioned at an equal distance (2 cm) from the beam center.

Shown in figures 2 and 3 are the biases and currents measured in a pulsed (2 ms, 10% duty), beam-generated plasma produced in 50 : 50 mixtures of Ar/SF_6. The applied bias consisted of a sinusoidal signal (20 kHz, 50 V peak to peak) across the transformer. In the configuration of figure 1, the plasma potential at the physical center of the plasma is close to the ground potential established by the slotted and termination anodes.

With no bias, the ion flux is small and isotropic, and the ion energy is limited by the ion temperature. With bias, the ion energy increases, and the ion flux grows and becomes anisotropic. The bias can be adjusted both in frequency and voltage. Frequencies above 1 MHz have little effect on the massive ions but can heat the light plasma electrons. Hence, a relatively low bias frequency of 20 kHz was used. The ion fluxes grow with bias voltage (up to the beam production rate), because the ions move faster and thus have less time to recombine. The ion energy increases almost directly with the bias voltage, as long as the sheath remains smaller than the ion mean free path. For that reason, a gas pressure below 100 mTorr was chosen. Since the ion fluxes become anisotropic at biases above several volts, anisotropic etching is possible. The etch rate can be increased by either increasing the applied voltage or raising the electron beam current to increase the plasma and reactive radical densities. However, the applied bias can also lead to electron heating, which can decrease the attachment rate in SF_6 or lead to electron impact

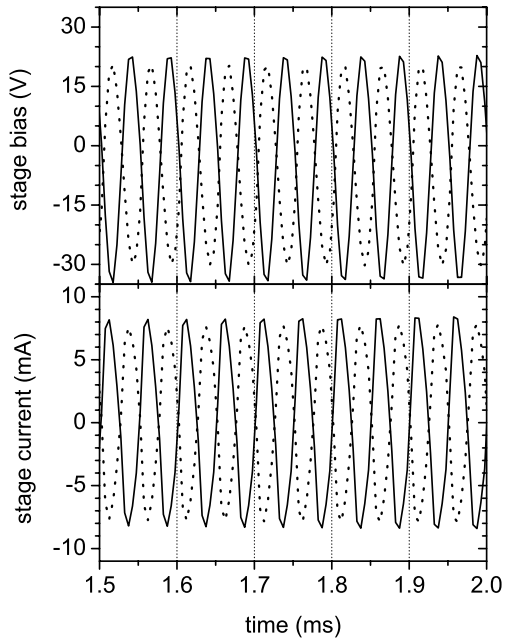

Figure 3. Measured voltages and currents in an ion–ion plasma produced in mixtures of argon and SF6 plasma using system of figure 1. For these measurements, the center tap of the secondary is floating (not grounded). Note the slight asymmetry in measured bias and symmetry in measured current.

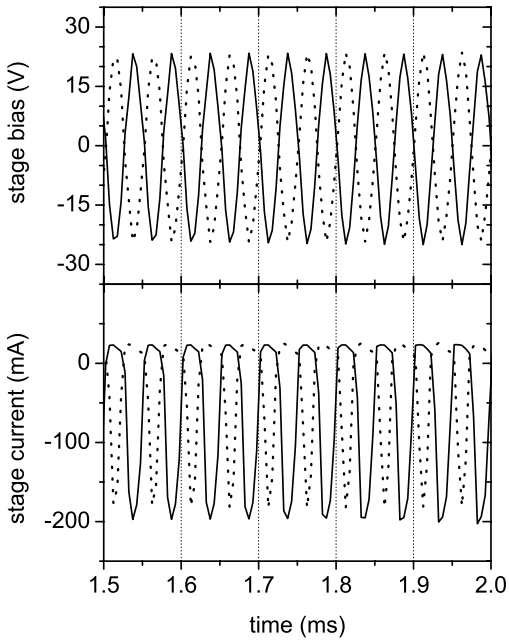

Figure 4. Measured voltages and currents in an argon plasma using the system of figure 1 where center tap of the secondary is grounded. Plasmas produced in argon will be electron-rich and thus the measured current is highly asymmetric when the applied bias is symmetric.

ionization. Indeed, the negative stage current increased and became notably noisy for peak to peak voltages above 400 V, which was attributed to electron current. Thus, high voltages should be avoided.

The stages used in the present experiments were placed at equal distances from the plasma center and had the same shape and area. Each stage received nearly equal fluxes of positive and negative ions, thus minimizing any charge accrued on the surfaces. To ensure that the fluxes are distributed uniformly across each surface, the standoff distance should be kept less than the stage radius. Moving the stages farther out reduces the ion fluxes (but not the fluxes of free radicals), because of losses to ion–ion mutual neutralization. In this work, the stages were located close to the beam edge in order to provide large ion fluxes at each stage. Midha and Economu [2] discussed a similar system consisting of an idealized ion–ion plasma located between two parallel plates. In their system one of the plates is driven by an ac signal while the other is grounded. In that configuration the plasma potential alternates in sign, while the fluxes of positive and negative ions alternate as discussed above. More recently, Meige *et al* [11] modeled a system containing two oppositely biased plates. The plasma potential remained near zero in that case.

The method of biasing the chucks was similarly critical to flux optimization. When the ac signal is applied through a transformer rather than a standard match box, the bias on each stage is 180° out of phase, which ensures that nearly equal fluxes of positive and negative ions are drawn from the plasma. The use of the transformer has other benefits as well, including the ability to evenly divide either the voltage amplitude or current amplitude by grounding or floating the center tap on the transformer secondary. Grounding the center tap ensures equivalent voltages amplitudes on either stage (figure 2), which is useful in applications that require identical energies at each chuck or substrate. Conversely, if the center tap of the transformer secondary is left floating (figure 3), each stage receives nearly the same flux of positive and negative ions during opposite voltage swings, independent of relative stage areas or standoffs. That is, the plasma will self adjust until the current is the same to each stage, and this is useful if there is a need for equal current without a strong need for equal ion energies. Note that the current and voltage magnitudes are nearly symmetrical about zero, whether the center tap is grounded (figure 2) or not (figure 3). Such behavior is possible only in ion–ion plasmas. Indeed, grounding or floating the center tap of the secondary will have little impact on ion–ion plasmas when the positive and negative ion masses are identical. The modest differences observed in currents in figure 2 and voltages in figure 3 result from the differences in positive and negative ion masses [11], which is the case for the gases used here [9]. By contrast, either the voltage or current is highly asymmetrical in electron-rich plasmas, as shown in figure 4, where the system of figure 1 was used with beam-generated plasmas produced in pure argon. In particular, the current is highly asymmetrical when the center tap of the secondary is grounded, because of the presence of a large electron current.

In summary, we have demonstrated an approach to extracting positive and negative ions from ion–ion plasmas and that the flux can be controlled in terms of energy and intensity. The approach needed to achieve this differs from conventional biasing techniques used in electropositive plasmas. Namely,

this technique employs a pair of electrodes arranged so that the ion–ion plasma is formed at the geometric center of the system, and a transformer is used to apply voltages across the plasma. This approach adds capabilities that are needed to fully realize the benefits of ion–ion plasmas in a number of applications.

Acknowledgment

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